Solar UV Irradiance Measurements from SUSIM UARS

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Abstract

The Solar UltraViolet Spectral Irradiance Monitor (SUSIM) aboard the Upper Atmosphere Research Satellite (UARS) has measured and continues to measure the solar UV irradiance since October 1991. This 13 year time period includes a secondary maximum of solar cycle 22, the ensuing solar minimum, the maximum of solar cycle 23, and into its declining phases. SUSIM maintains the calibration of its changing responsivity through a combination of measurements of four stable onboard deuterium calibration lamps and measurements of infrequently exposed reference channels. The wavelength-dependent UV irradiance time series exhibit two dominant periodicities, that of solar rotation (27 days) and solar cycle (11 years). The solar cycle variation of the UV irradiance was similar for solar cycles 22 and 23, about 55% at Ly-α, about 7% at 205 nm, and less than 1% above 300 nm. The SUSIM measurements are compared with other coincident measurements including those measured by SOLSTICE over a similar time period and with the Mg II core-to-wing ratio index. Prospects and requirements for continued and possibly improved monitoring of the solar UV irradiance are discussed.

Background and Overview

The solar UV irradiance, the spectral sum of radiant flux over the solar disk, plays a central role in the structure of the terrestrial atmosphere. All of this radiation below about 290 nm is absorbed in the atmosphere, principally by ozone and molecular oxygen. This absorption of energy warms the stratosphere. The solar UV irradiance does vary as a result of solar activity.

The discovery of the Antarctic ozone hole in the 1970s and the possible causal role of CFCs led to the formulation of the Upper Atmosphere Research Satellite (UARS) mission. Because the solar UV irradiance both creates and destroys ozone, a comprehensive study of this problem required the measurement of the solar UV irradiance from space.

Two experiments were chosen to make these measurements aboard UARS, the Solar-Stellar Intercomparison Experiment (SOLSTICE) and the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM).

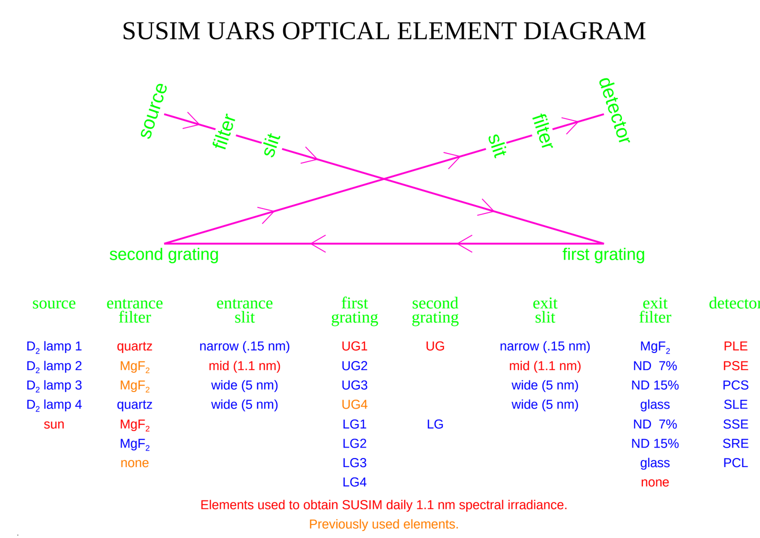
Experiment Description

Accurate measurements of solar UV spectral irradiance have proved to be difficult to obtain because the intense solar UV flux causes degradation of the responsivity of the measuring instruments. Accordingly, instruments making long-term solar UV measurements must provide a means of in-flight calibration. SUSIM does this through measurements of four stable deuterium lamps and by infrequent measurements by redundant optical channels. The reduced UV exposure of these redundant channels allows for correction of the working channel responsivity.

SUSIM is a dual dispersion, dual-spectrometer instrument which scans UV wavelengths (108–412 nm). The optical path of is displayed below in a conceptual view of the SUSIM instrument. Either the sun or one of four deuterium lamps illuminate either spectrometer each of which has available a choice among four primary gratings and a single secondary grating. The remaining elements in the optical path can be configured at will to accomplish the measurement goals. Three measurement resolutions (5 nm, 1.1 nm, and 0.15 nm) are available through the choice of entrance and exit slits. Seven entrance filters (including "none"), seven exit filters (again, including "none"), and seven detectors are separately selected for each wavelength scan. In most cases, these selections are made to be compatible with wavelength range and signal levels.

SUSIM Acronyms

oSC	- old Standard (working) Channel
nSC	- new Standard (working) Channel
RC	- Reference Channel
nRC	- new Reference Channel
MoRC	- Monthly Reference Channel
MiRC	- Mission Reference Channel
LMiRC	- Lower Mission Reference Channel
Qx	- Quartz Filter x
Mx	- Magnesium-Fluoride Filter x
UGx	- Upper Spectrometer, Grating x
LGx	- Lower Spectrometer, Grating x
PSE	- Primary Short wavelength Electrometer
SSE	- Secondary Short wavelength Electrometer
PLE	- Primary Long wavelength Electrometer
SLE	- Secondary Long wavelength Electrometer
SRE	- Secondary Reserve (short wavelength) Electrometer



Two scans over wavelength ranges 108–264 nm and 234–412 nm at 1.1 nm resolution using subchannels having slightly different optical elements constitute SUSIM's principal daily measurement. The optical elements used to make these measurements have changed several times during the course of this 13+ year experiment as is shown in the following table.

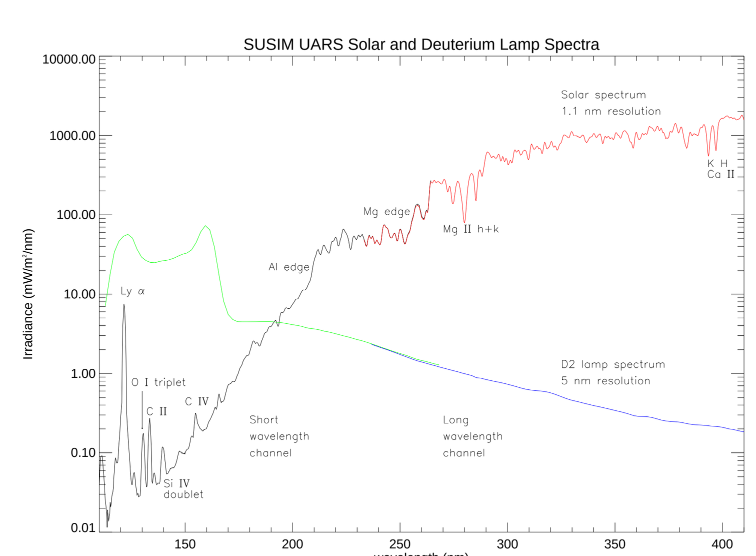
SUSIM Working Channel Optical Elements

entrance filter	slits	wavelength range (nm)	grating pair	exit filter	detector	date
MgF_2-1	MM	108–264	UG4	none	PSE	10/11/91
quartz-1	MM	234–412	UG4	none	PLE	10/11/91
none	MM	108–264	UG4	none	PSE	2/23/94
MgF_2-2	MM	108–264	UG1	none	PSE	3/14/99
quartz-1	MM	234–412	UG1	none	PLE	3/14/99
MgF_2-3	MM	108–264	UG1	none	PSE	7/02/03

In each case, loss of responsivity at wavelengths shorter than 160 nm in the short wavelength working channel was the reason for the change. The long-wavelength subchannel was also changed 1999 so that the same grating pair would be used for the short- and long-wavelength scans, thus reducing the wear on the grating mechanism. The scan of the wavelength region surrounding the strong Mg II absorption feature near 280 nm is also performed daily. In contrast to the daily 1.1 nm resolution scans, the Mg II are collected using the original elements which comprised the daily long-wavelength subchannel. Important spectral features (e.g. Ly-α, Mg II, and C IV) are also scanned daily at high (0.15 nm) resolution. A fully high resolution scan was performed weekly until ???; afterwards, these scan are performed about four times per year.

UV Irradiance Spectra of the Sun and Lamps

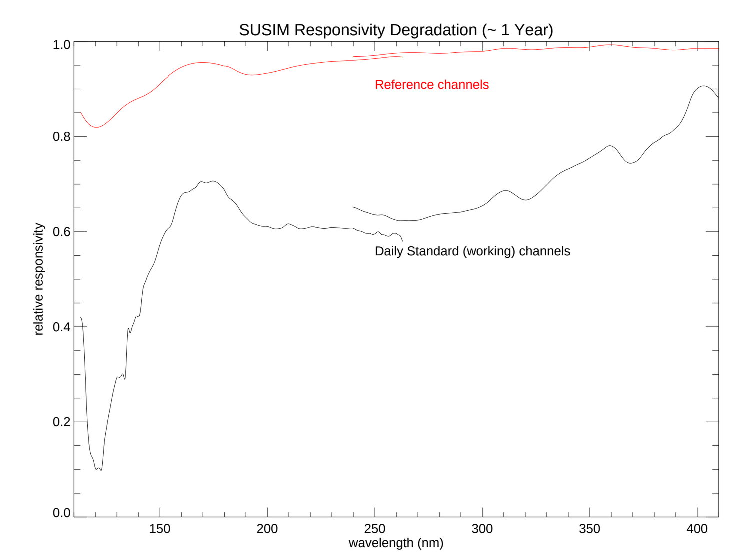
The figure below displays the solar UV irradiance spectrum as measured by SUSIM's daily 1.1 nm channels for 1 February 1992. Although the solar spectrum is far from fully resolved at this resolution, its basic features are apparent. At the shortest wavelengths, the spectrum is characterized by a weak continuum and strong emission lines that emerge from the transition region and chromosphere. For longer wavelengths approaching and somewhat above the temperature minimum at about 160 nm, the strength of the continuum increases exponentially. Above the temperature minimum, the emission lines give way to absorption lines. At about 208 nm, the solar irradiance rises abruptly at the Al edge. At still longer wavelengths and for the remainder of the UV spectrum, the absorption lines become so numerous that the spectrum can be characterized as a line-blanketed continuum.



The figure above also shows the deuterium lamp spectrum at low (5 nm) resolution. Not resolved in this spectrum is the two regions containing several strong emission lines at about 125 nm and 160 nm.

Responsivity Degradation Calibration

The responsivity of the SUSIM working channel degrades strongly especially at shorter wavelengths. Further, this degradation increases monotonically with UV exposure for all wavelengths. The figure below provides an example of this behavior during the first year of SUSIM experimental measurements. The black curve shows the wavelength-dependent relative responsivity (i.e. the ratio of responsivity at the end of the period to that of the beginning) of the two working subchannels after one year of daily exposure. The red curve shows the same for a reference channel which was exposed only twice over that period. Such strong changes in instrumental responsivity must be accounted for in order to calculate accurate solar irradiances.



All optical elements used in the SUSIM experiment appear to degrade except, of course, the slits (Floyd et al., 1998). The mechanism for this degradation is understood to be polymerization of hydrocarbon contaminants on optical surfaces. Consistent with the experience of the aggregate degradation of the optical channels, elements receiving more UV exposure degrade faster than those receiving less. Accordingly, the primary gratings degrade more quickly than the secondary gratings. Also for the same reason, the elements downstream of the gratings (i.e. exit filters and detectors) degrade much more slowly than do the entrance elements. The deuterium calibration lamps also degrade. Prelaunch experience indicates that polymerization darkens the exit window of these otherwise stable lamps.

SUSIM Reference Optical Channels

Optical Channel	Grating Pair	Entrance Filters	Detectors	Uses	Time Period (UARS days)
RC	UG1	M1/Q2	SSE/SLE	15	31–2740
nRC	LG2	M1/Q2	SSE/SLE	6	2741–present
MoRC	UG2	– / –	PSE/PLE	98	316–present
MiRC	UG3	– / –	SSE/SLE	7	1368–present
LMiRC	LG3	– / –	SRE/SLE	3	2741–present
SRC	UG4	– /Q1	PSE/PLE	36	2741–present

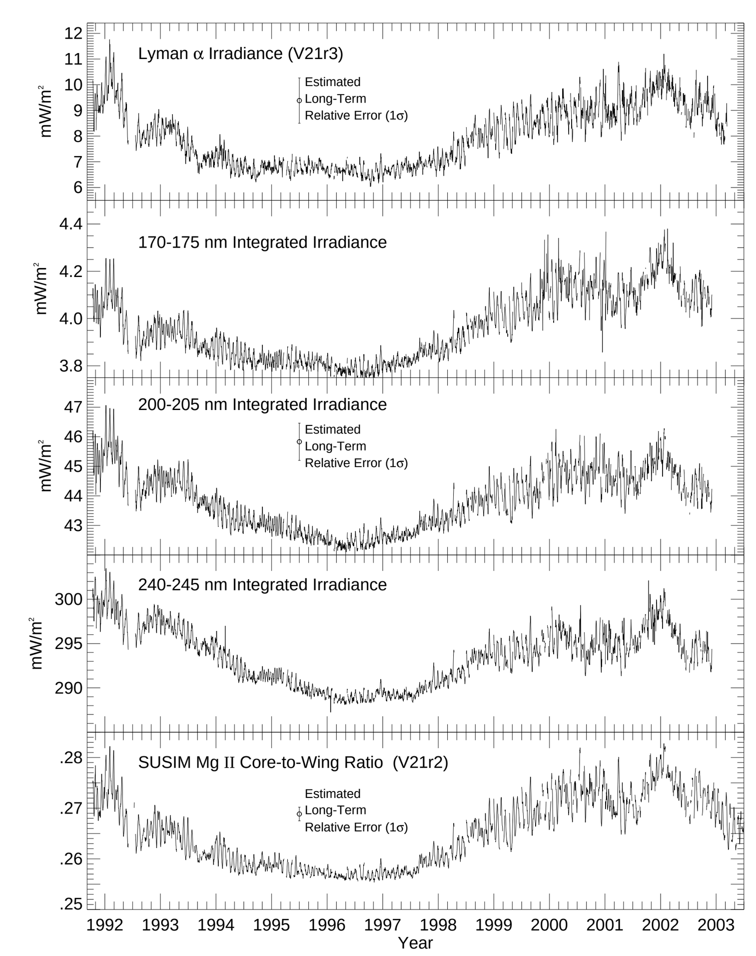
The degradation of the lamps is calculated through intercomparison of nearly simultaneous measurements of each lamp by the same optical channel. Because the usage rates of the lamps are different, the assumption that the degradation is only a function of usage can be used to solve for the changes in lamp output. For each lamp, the same calibration scans are performed during the usage of each lamp. Measurements of the lamps, corrected for lamp output degradation, are then used to correct the measurements of the refrence channels which have been used very infrequently and thus seen little UV exposure. The calibration of the working channel is then determined through intercomparison of nearly simultaneous solar scans by the working and reference channels.

SUSIM Deuterium Lamp Usage

Lamp	Nominal Rate	Actual Uses
1	quarterly	36
2	biannually	24
3	monthly	121
1	yearly	12

UV Spectral Irradiance Time Series

Displayed below are UV irradiance time series derived from solar UV spectral irradiance measurements made by the SUSIM experiment. Please note that the solar UV irradiance rises by nearly five orders of magnitude from short to long wavelengths. The Ly-α flux is strength of the H I line at 121.6 nm. The Mg II index is the irradiance ratio of the core and wings of the strong Mg II absorption feature near 280 nm. The remaining three time series are the integrated fluxes for 170-175 nm, 200–205 nm, and 240–245 nm wavelength bins. We display 5 nm bins in order to reduce noise.



The time series share a number of similarities including a marked correspondence with the level of solar activity. SUSIM began making measurements at the end of the solar cycle 22 maximum in 1991. These extend through the following solar activity minimum, through the solar cycle 23 maximum, and into its descending phase. The long-term behavior of the displayed SUSIM time series is a result of the solar activity cycle. Additionally, for most time periods, the time series exhibit an unmistakeable 27-day periodicity which is a result of the solar rotation. This is the time period over which bright regions on the solar surface transit the solar disk and return to their original position (as viewed from the Earth). Generally, the strength of the solar rotation modulation is weakest for solar minimum, apparently because there are fewer bright regions that can contribute to irradiance variations during solar mimimum. In contrast to time series of Total Solar Irradiance (TSI), the UV irradiance time series do not exhibit the large dips that are associated with sunspot groups near disk center. Rather, irradiances for UV wavelengths up to 263 nm corresponding to the solar transition region, chromosphere, and upper photosphere, appear to be affected only by bright features on the solar disk.

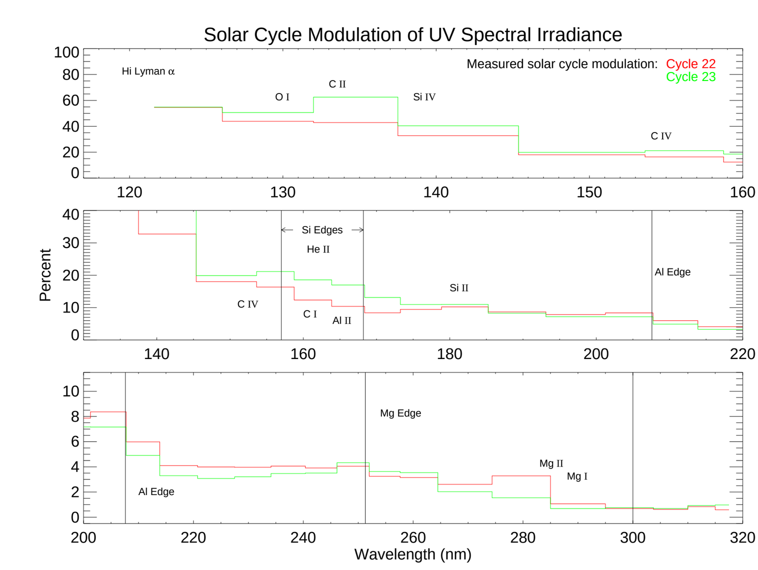
Occasionally, such as the six month period beginning in November 1994, 13.5-day periods are predominant in some time series. Differences in the center-to-limb variation of active region radiance for different wavelengths can cause this behavior when bright regions are separated by 180° (Crane et al. 2004).

Solar Cycle Variation

Because SUSIM UV spectral irradiance measurements extend from near to the maximum of solar cycle 22 through the maximum of solar cycle 23, estimates of the wavelength-dependent solar cycle variation of irradiance can be established. We could also establish the solar rotation modulation of irradiance, but sincethis depends on the distribution of active regions on the solar disk and not on their number, this is more difficult to interpret meaningfully. Calculation of the solar cycle modulation of the solar UV irradiance can be performed in several ways. Here we present the results of two different methods. Method 1 is performed on each UV irradiance time series as follows:

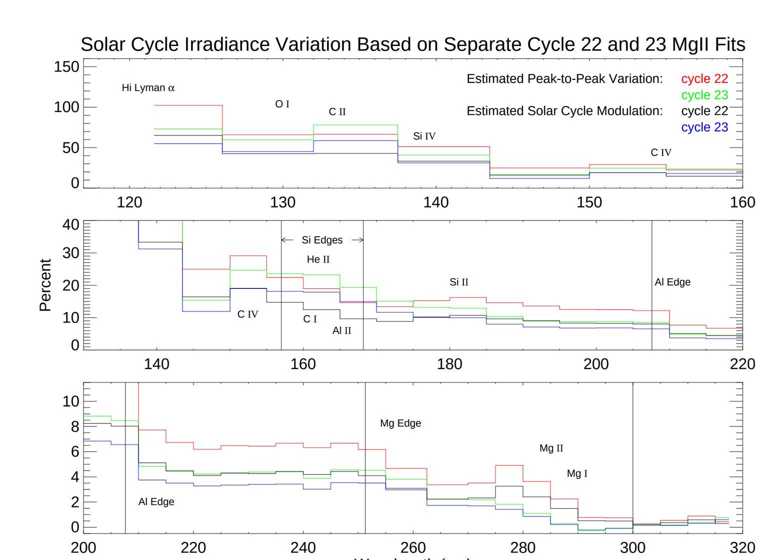
1. convolve with a 81-day FWHM Gaussian function to remove solar rotation and noise variations.
2. find the maximum before (cycle 22) and after (cycle 23) 1996
3. find the minimum before 2000
4. solar cycle variation is its maximum to minimum quotient minus one

The results of Method 1 are displayed in the three panels of the figure below.



We bin the wavelengths in 5-10 nm regions in order to reduce the effect of wavelength error on the results. Below 142 nm, only bins centered on the four strong emission lines, Ly-α, O I, C II, and Si IV, can be distinguished. Except for a few wavelength ranges, the measured solar cycle variation is similar for solar cycles 22 and 23. Of course, this method likely does not fully account for the variation during cycle 22 whose peak occurred before the start of SUSIM measurements in 1992. In any case, the variation is relatively the largest for the shortest wavelengths, e.g. 50% for Ly-α. The variation falls for longer wavelengths down to about 8% just above the Al edge. For wavelengths between the Al edge and the Mg edge near 252 nm, the solar cycle variation is roughly constant, about 4%. The variation falls for wavelengths above the Mg edge until no significant variation is found at about 290 nm above the estimated uncertainty of about 2%. Divergences in the solar cycle variability between the two solar cycles in the 155–175 nm and 275-285 nm ranges are not likely to be significant.

Method 2 utilizes the well known relationship between the Mg II index and UV spectral irradiances. The Mg II index is understood to be more stable (both in the short and long term) than measurements of the spectral irradiances. Further, solar UV measurements thus far indicate that they have a linear relationship with the Mg II index. Accordingly, fitting each UV irradiance time series with the Mg II index and then deriving the solar cycle variation from the Mg II fit may generate a better estimate. The figure below shows the results of this approach.



Included also is the peak-to-peak variation for each wavelength bin. The peak-to-peak variations are larger because the solar rotation amplitudes provide additional variation. Using Method 2, we find that the estimates of the wavelength-dependent solar cycle modulation variation are similar to that found by Method 1.

Data Access and Documentation

The SUSIM data are freely available in a number of forms over the internet. The level 3 product (L3BS) contains the solar UV spectral irradiances integrated over each 1 nm as well as solar indices. It may be obtained from the GSFC DAAC:

`http://daac.gsfc.nasa.gov/`

or from the SUSIM ftp site:

`ftp://susim.nrl.navy.mil/pub/uars/`

Both of these may be reached though SUSIM's WWW site:

`http://wwwsolar.nrl.navy.mil/susim_uars.html`

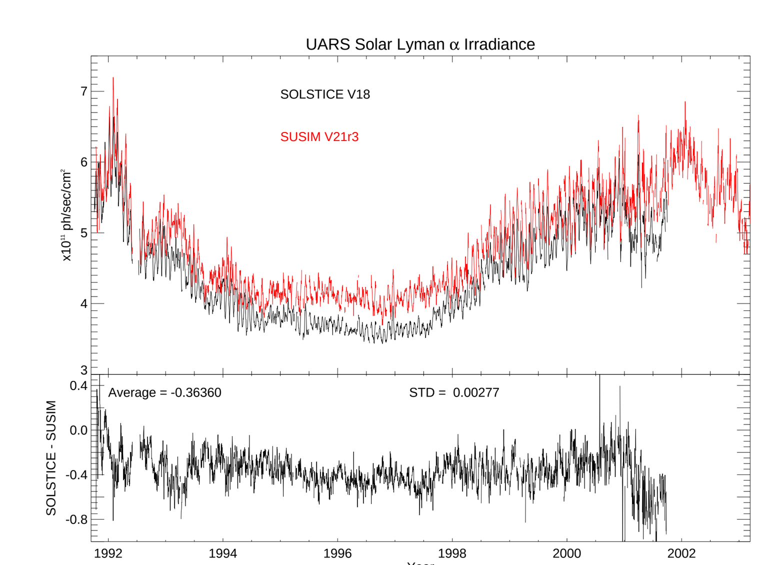
(More up-to-date versions of the Mg II index and Ly-α irradiance are available elsewhere; see below.) Also available from the ftp site is the SUSIM daily 1.1 nm resolution spectral irradiances on the instrumental wavelengths and at the instrumental resolution. The Mg II index (current version V21r2) is updated within a few days after the base measurement. It is also available from the SUSIM ftp site. An update (V21r3) of the SUSIM Ly-α irradiance is also available from the SUSIM ftp site.

Plans and Prospects

SUSIM aboard UARS has made solar UV irradiance measurements for more than 13 years. Given that the UARS spacecraft is aging, the end of SUSIM measurements is near. Fortunately, these measurements will be continued by the Solar Irradiance Monitor (SIM) and SOLSTICE II aboard the SOlar Radiation and Climate Experiment (SORCE).

There are two goals that remain for the SUSIM experiment. First, is to complete the ongoing revision of the degradation calibration and extend it to the end of the mission (whenever that might occur). Second, the SUSIM data needs to be intercompared with that of the two SORCE experiments as well as with UARS SOLSTICE. It is expected that these two tasks will be completed by the end of calendar year 2005.

As an example of comparisons that will be done over broad UV wavelength ranges, the figure below displays the Ly-α (121.6 nm) irradiance from SUSIM (V21r3) and from SOLSTICE UARS (V18). Below is plotted the difference between the two in absolute units. After highly variable differences during the first three months, the two eventually maintain a constant difference until 2001. After removing the average difference, the standard deviation between the two is about 1%.



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